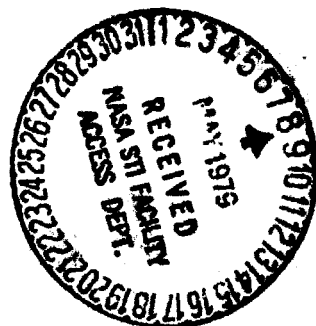
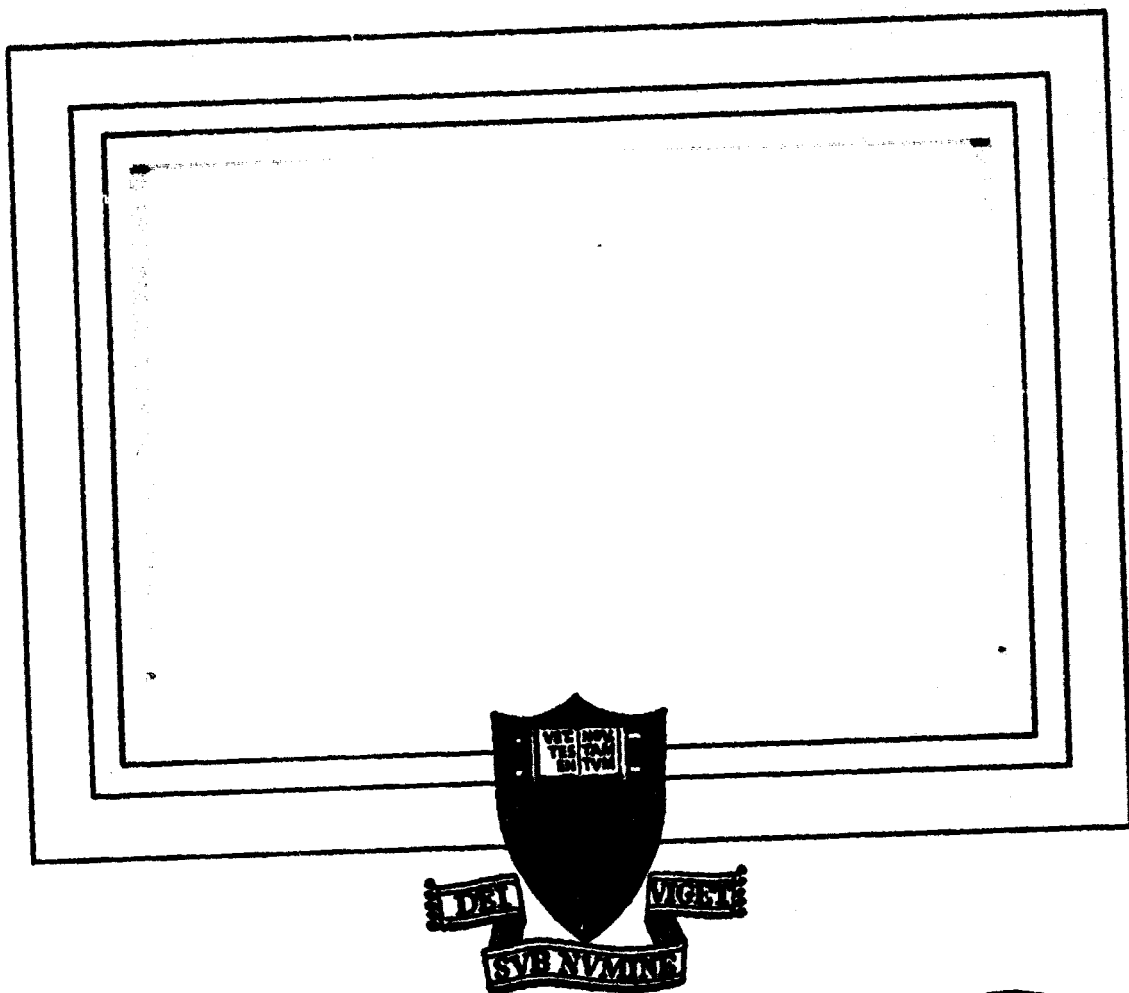


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# PRINCETON UNIVERSITY

(NASA-CR-158478) LARGE AREA CCD IMAGE  
 SENSORS FOR SPACE ASTRONOMY Final Technical  
 Report, 1 Nov. 1977 - 28 Feb. 1979  
 (Princeton Univ. Observatory) 16 p HC  
 A02/MF A01

N79-22981

inclas  
 CSCI 03A G3/89 14750

PRINCETON UNIVERSITY OBSERVATORY  
Princeton, New Jersey 08540

FINAL TECHNICAL REPORT

"LARGE AREA CCD IMAGE SENSORS FOR SPACE ASTRONOMY"

NSG 7379

Period: November 1, 1977 to February 28, 1979

Submitted to:

National Aeronautics and Space Administration  
HEADQUARTERS, Washington, D.C.

Principal Investigator: Martin Schwarzschild.

Martin Schwarzschild

April 6, 1979

## TABLE OF CONTENTS

Introduction

Description of the CCD Television Camera

Rockwell CCD

Laboratory Tests of Rockwell CCD's

Summary

LIST OF FIGURES

- Figure 1      CCD Camera Head Assembly
- Figure 2      CCD Camera Head Assembly, Control Electronics and LN<sub>2</sub> Dewar
- Figure 3      Rockwell CCD No. 1, Resolution
- Figure 4      Rockwell CCD No. 1, Dark Current
- Figure 5      Rockwell CCD No. 1, Vertical Charge Transfer Inefficiency
- Figure 6      Rockwell CCD No. 2, Dark Current Exposure

FINAL REPORT

"LARGE AREA CCD IMAGE SENSORS FOR SPACE ASTRONOMY"

INTRODUCTION

The Defense Advanced Research Projects Agency (DARPA) has a substantial program with Rockwell International to develop a 2200 x 2200 pixel CCD mosaic array made up of 400 individual CCD's, 110 x 110 pixels square. This type of image sensor appeared to have application in space and ground-based astronomy.

Under this grant, NSG 7379, Princeton has built a CCD television camera system capable of operating an array of 4 Rockwell CCD's to explore the suitability of the Rockwell CCD for astronomical applications. The equipment we have built is flexible enough in its design to allow Texas Instruments and RCA type CCD's to also be operated with a minimum of modification. Rockwell agreed to supply CCD's for this evaluation at no cost to this grant. Two individually packaged CCD's from Rockwell have been received and evaluated by Princeton.

While we are very encouraged by our evaluation of the basic characteristics of the best individual Rockwell chips, Rockwell has recently found that their yield in manufacturing this design is too low to supply sufficient CCD's for the DARPA mosaic array. We understand that Rockwell has initiated a design improvement program extending over the next 9 months in an effort to increase the yield. There appears to be little likelihood that Rockwell will be able in the near future to provide Princeton with the 4 CCD array originally contemplated. The potential utility of large mosaic arrays in astronomy is still substantial and one should continue to monitor Rockwell's progress in the coming year.

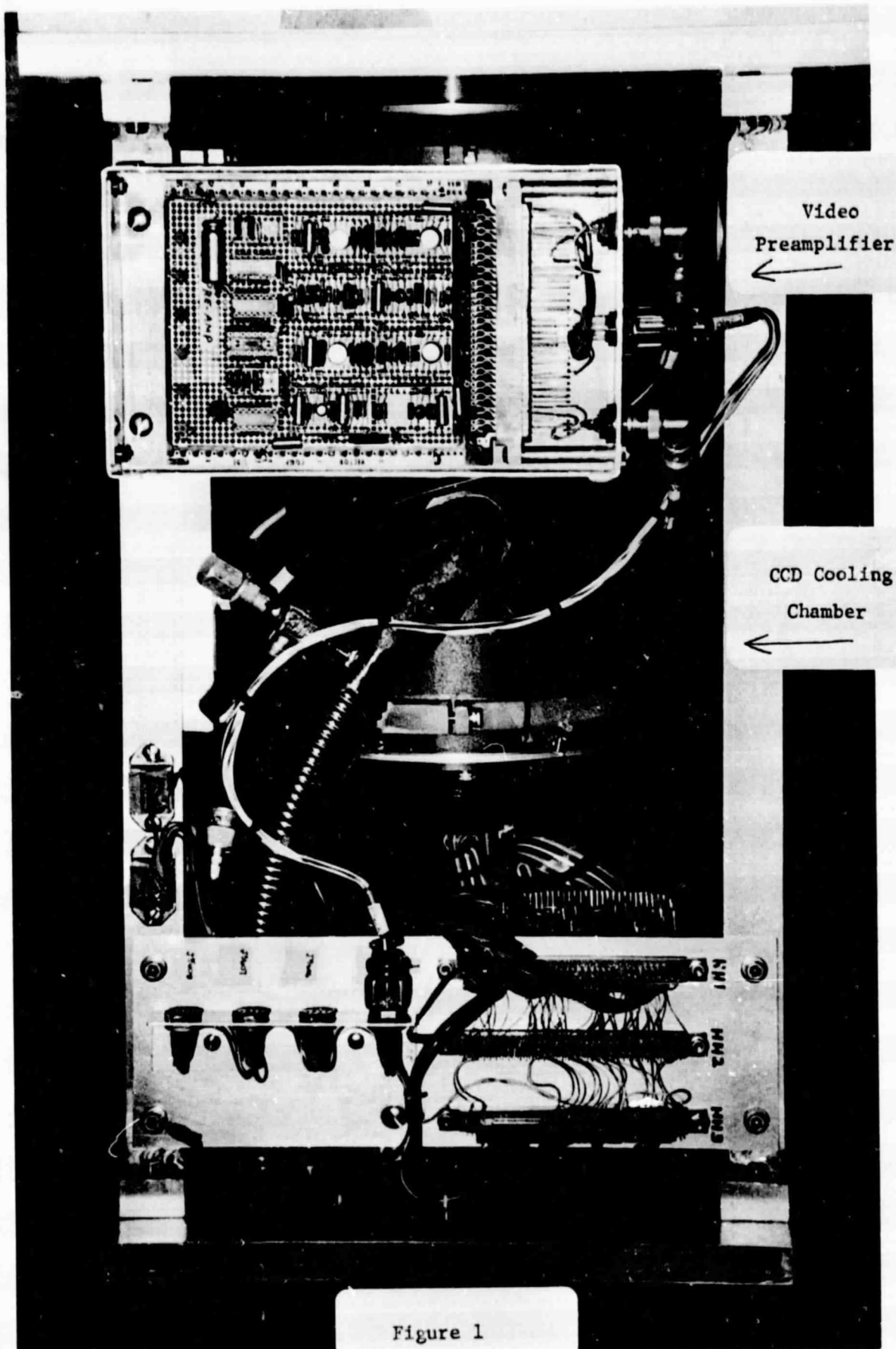
In addition to the Rockwell CCD evaluation we have operated both RCA and Texas Instruments CCD's in the CCD camera. The RCA CCD was 3-phase with 512 x 320 pixels, similar to the RCA SID-52501. These preliminary tests of this developmental CCD were encouraging. The Texas Instruments CCD was their 3-phase, back illuminated 100 x 160 pixel CCD. The system with this CCD is now operating at the Princeton 36" reflector as the image sensor following a Fabry-Perot narrow band filter.

#### DESCRIPTION OF CCD TELEVISION CAMERA

The CCD television camera was designed to operate 4 of the 4 phase, "P" type Rockwell 110 x 110 pixel CCD's. Its design is flexible enough to also allow the RCA and Texas Instruments 3 phase CCD's made with N type silicon.

Figure 1 shows the CCD camera head assembly without its light shield. The head assembly includes a liquid nitrogen cooled Products for Research photomultiplier housing that can be cooled to  $-125^{\circ}\text{C}$  with the CCD installed. Video amplifiers and some of the CCD drive electronics are also located in this head assembly.

Figure 2 shows the CCD camera head assembly mounted on the telescope behind the offset guiding assembly and a Fabry-Perot narrow band filter.





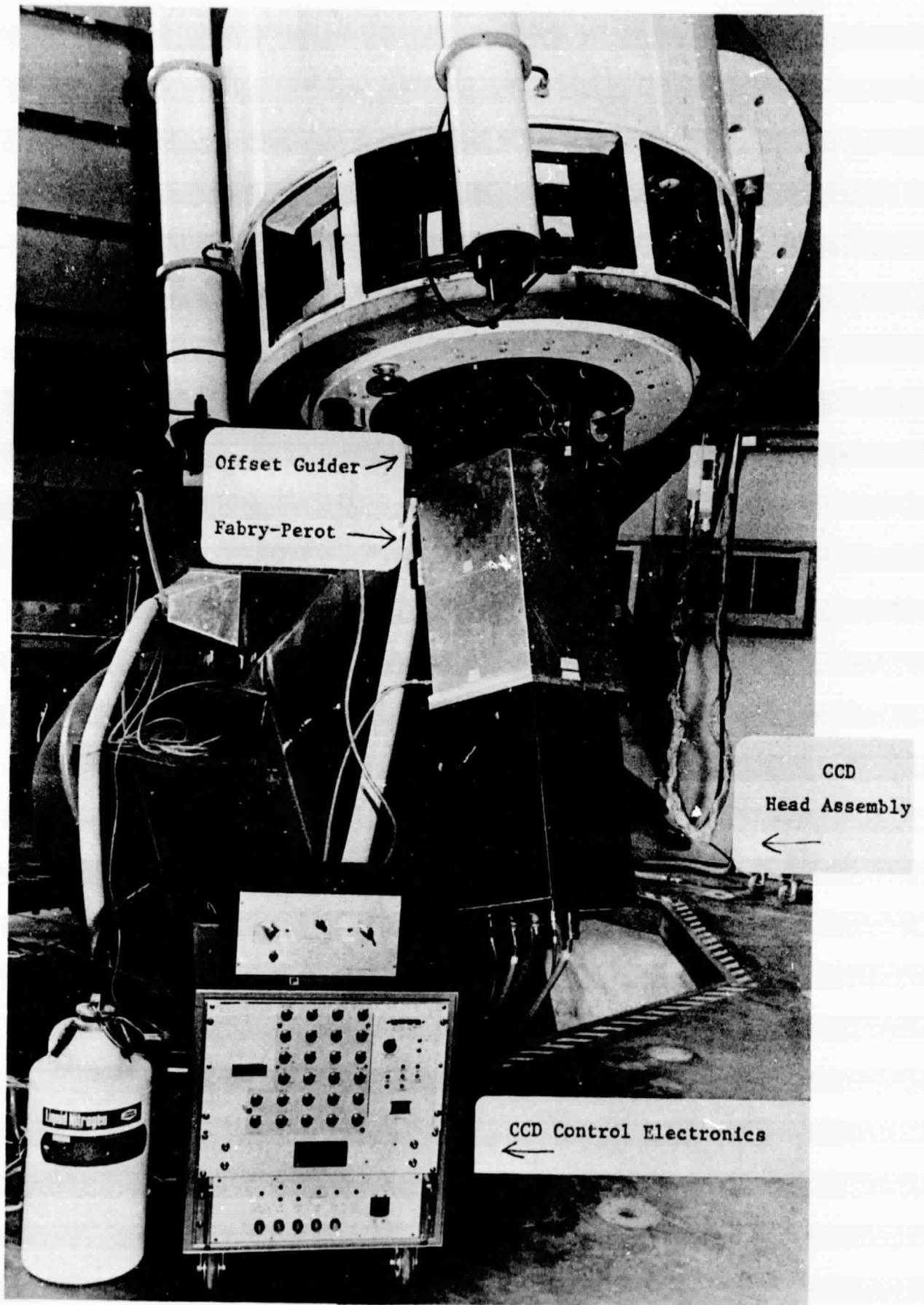


Figure 2

The CCD electronics control assembly is connected via 6 meter cables to the head assembly. The CCD electronics control assembly is connected to the OBSCAM data acquisition system via 67 meter long cables.

The CCD readout rate is  $10^5$  pixels per second. The data is digitally recorded with 12 bit accuracy. Details of the OBSCAM system can be found in the final report on Contract NAS5-22989. Details on the CCD camera design and construction can be obtained by writing to Princeton University Observatory, Department of Astrophysical Sciences, Princeton, New Jersey 08544.

#### ROCKWELL CCD

The Rockwell CCD is front illuminated, has  $110 \times 110$  pixels and the pixel size is 46 microns square. The CCD is scanned out with four phase clocking of the electrodes. It differs from other CCD's in that Rockwell uses "P" type silicon for the bulk material.

The CCD's are laid out so that the CCD spacing in the mosaic has gaps  $300 \mu$  wide along each row. The space between rows is 2.9 mm such that the total active area is 60% of the 4" x 4" square area subtended by a  $2200 \times 2200$  pixel array.

#### Laboratory Tests of Rockwell CCD's

Rockwell CCD No. 1 (Rockwell No. 30273-SSTSD-12-14-F4)

##### 1) Charge Sensitivity

The charge sensitivity of the on-chip amplifier was measured by projecting a uniformly illuminated  $84 \times 78$  pixel rectangle onto the CCD. During readout an electrometer measured the current at the drain of the precharge field effect transistor on the CCD chip. The chip temperature during the measurement was  $-90^\circ\text{C}$ . The measured charge sensitivity at the chip output was  $1.8 \mu\text{V}/\text{electron}$ .

## 2) Full Well Capacity

The maximum well capacity before degradation of resolution was  $1.3 \times 10^6$  electrons/pixel.

## 3) Readout Noise

The total readout noise for this chip in our system was 153 electrons/pixel (peak-to-peak) or approximately 30 electrons/pixel (RMS). The readout rate is  $10^5$  pixels/second.

## 4) Resolution

Figure 3 shows a single line near midframe in the readout of a resolution test chart image. The CCD was operating at a temperature of  $-126^\circ\text{C}$ . The chart consisted of square waves with periods equal in width to 1, 2, and 3 pixels, followed by a 12 pixel white patch which is bisected by a 1 pixel black line, and then a 9 pixel black patch. There is no resolution of the 1 pixel width pattern (as expected). The 2 pixel width pattern shows modulation of 15% of the black to white difference, and the 3 pixel width pattern shows 20% modulation. The actual resolution response of the chip may be higher than these measurements suggest, for the phase of the square wave pattern with respect to the pixels is uncontrolled, and there was a window of dubious quality in the optical path. The phase effects can be computed for the three pixel width pattern, and the corrected modulation for this pattern is approximately 25%. This is still a lower limit, however, because of the problem of the window.

## 5) Dark Current

Figure 4 shows the dark current variation with chip temperature. The dark current was measured in areas not affected by blemishes (see following discussion). The dark current is less than 0.1 electron/pixel/second at  $-125^\circ\text{C}$ . The error estimates shown were obtained in the standard way by comparing several different dark exposures taken at the same temperature.

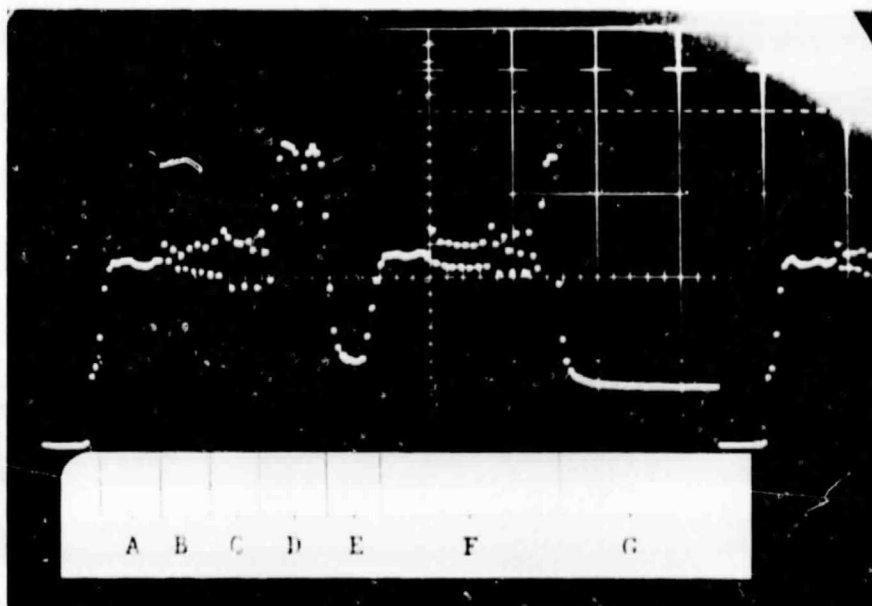


Figure 3

Rockwell CCD No. 1 resolution.

- A: 1 pixel period square wave
- B: 2 pixel period square wave
- C: 3 pixel period square wave
- D: 12 pixels white (bisected by 1 pixel black line)
- E: 9 pixels black
- F: pattern repeats
- G: 30 pixels overscan

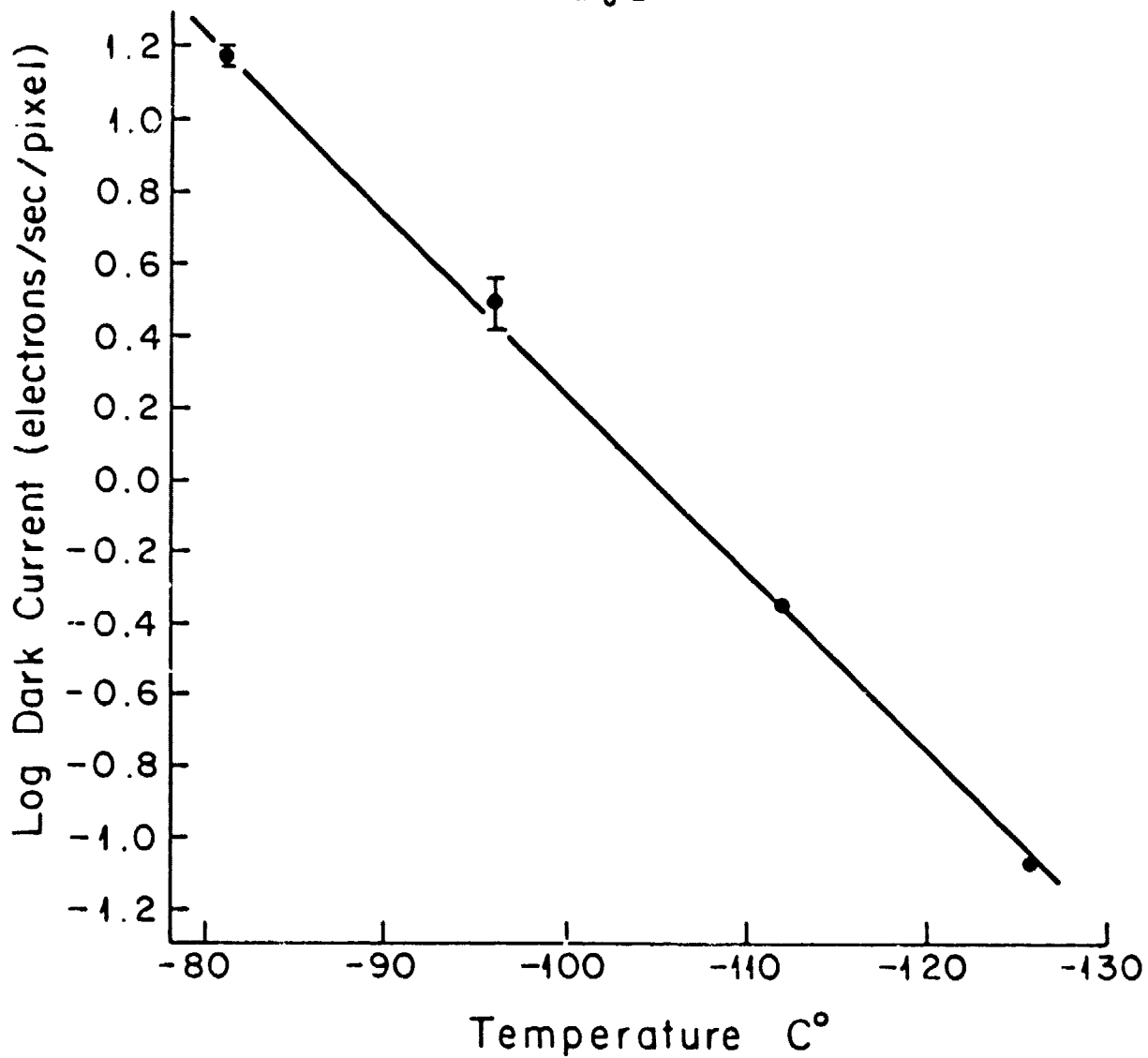


Figure 4

Rockwell CCD No. 1      Dark Current

Dark current in portions of chip not affected by defects.

No error estimates are available for last two points.

## 6) Blemishes

There are three single pixel defects in this chip which are nonthermal in nature, that is, defects that do not reduce with cooling. In a 1 hour exposure each of these defects blooms, fully saturating approximately 20 neighboring columns.

## 7) Charge Transfer Efficiency

At room temperature the charge transfer efficiency is good everywhere on the chip. However, at all cooled temperatures we investigated ( $-75^{\circ}\text{C}$ ,  $-90^{\circ}\text{C}$ ,  $-105^{\circ}\text{C}$ ,  $-125^{\circ}\text{C}$ ) the last 25 columns of the device lose vertical charge transfer efficiency. The image in these columns is smeared vertically through the entire column. Figure 5 shows this effect; it shows a line in the entirely white area of the test chart image approximately six lines below the resolution pattern. At the right, the smeared image of the square wave resolution pattern is seen. If there were no transfer inefficiency, this portion of the line would be at a uniform white level, as on the left side of the line.

Rockwell Chip CCD No. 2 (Rockwell No. 30273-SSTSD-19-2-E1)

This chip has approximately six non-thermal defects of the type discussed above. These defects bloom approximately 10 pixels up and down their respective columns in a few minutes. At all cooled temperatures there is a horizontal charge transfer inefficiency when the exposure is less than 10% of full well. This smears the image horizontally, including the blooming charge from the defects. This combination of effects rapidly fills the entire chip with dark current. Figure 6 shows the readout of an entire frame of a 15 minute dark exposure at  $-126^{\circ}\text{C}$ . The horizontal scale in this figure is compressed by a

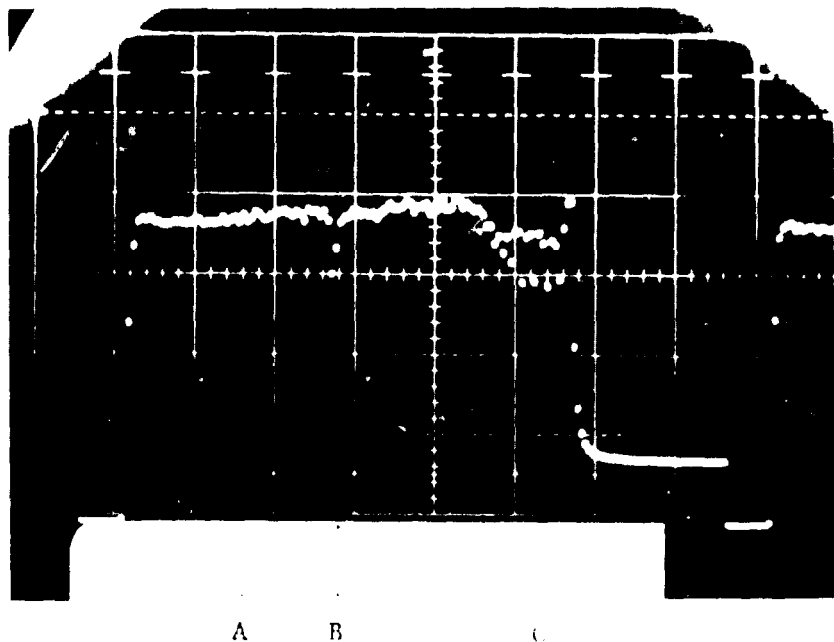


Figure 5

Rockwell CCD No. 1 vertical charge transfer inefficiency

A line in the white area of the resolution chart.

A: white image

B: 1 pixel black line in image

C: image of resolution pattern smeared vertically  
c.f. Figure 3.

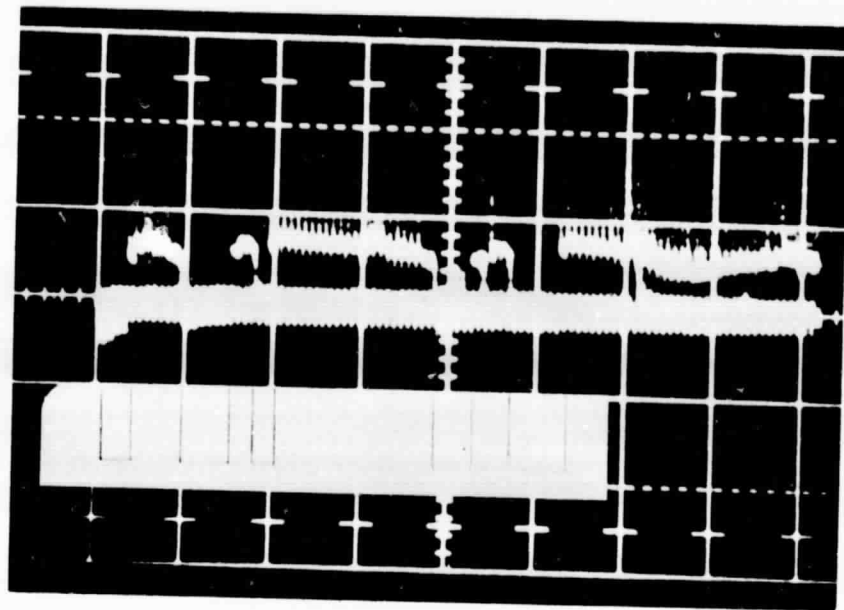


Figure 6

Rockwell CCD No. 2

Full frame of a 15 minute dark exposure at  $-126^{\circ}\text{C}$ . Most of chip contains smeared dark current from nonthermal defects. Only areas marked are clear (about 28% of area). In slightly longer exposures these areas would also be affected.



factor of 100 compared with Figures 3 and 5; thus all 100 lines of the image are shown, arranged end to end. Ideally, the dark current in all the lines should be low, as in the marked areas. Approximately 72% of the image has been contaminated with excessive dark current. In slightly longer exposures the entire chip is filled. Hence, this chip is greatly inferior to Chip No. 1 for astronomical applications.

#### SUMMARY

We feel that the Rockwell CCD shows considerable promise for astronomical applications. In the good areas of chip No. 1 (approximately 60% of the total chip area) the charge sensitivity, full well capacity, readout noise, resolution, and dark current characteristics are very good. These portions of this chip would make an excellent astronomical detector. However, the nonthermal blemishes and charge transfer inefficiency at low temperature reduce the yield of usable chips to the point where these problems must be solved by Rockwell before these chips will become useful devices for astronomy.